Garnet sector and oscillatory zoning linked with changes in crystal morphology during rapid growth, North Cascades, WA

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Abstract

Metamorphic garnet with sector zoning in the cores and oscillatory zoning in the rims grew during rapid heating of pelitic rocks in the Chiwaukum Schist. Both types of compositional zoning are exemplified by sharp, but low amplitude, boundaries between broad petal-shaped sectors and between narrow concentric zones, respectively. Zoning is most obvious in calcium, which is inversely correlated with iron and magnesium content. Garnet habit inferred from the oscillatory calcium zoning and external morphology indicates a growth transition from early crystal forms with both trapezohedral and dodecahedral forms to later crystal forms dominated by trapezohedral faces. This transition is accompanied by changes in compositional sector zoning and may reflect the roles of local growth dynamics and external forcing mechanisms affecting growth of garnet. Subsequent modification of these textures produced patchy zoning in calcium. Electron backscatter diffraction confirms the inferred crystal growth habits and that compositional zoning occurs within single garnet crystals.

Exchange thermobarometry and the peak mineral assemblages indicate that metamorphic conditions reached 640-650°C at 6.5-8.0 kbar. These temperatures are sufficient to allow significant volume diffusion; therefore, preservation of the finely banded compositional zoning in garnet requires rapid heating and cooling. Garnet Sm-Nd ages and indistinguishable zircon U-Pb ages from adjacent orthogneiss bodies confirm that garnet grew rapidly during localized and short-lived heating adjacent to sill-like intrusions of tonalite.

Introduction

Equilibrium thermodynamics is commonly used to predict the pressure, temperature, and fluid composition in rocks (e.g., Spear, 1993). These studies, particularly many of garnet, have led to numerous advances in mineralogy, petrology, and tectonics. However, disequilibrium processes may be important in many rocks (e.g., Wilbur and Ague, 2006). Observation of unambiguous textural and compositional features indicating disequilibrium during metamorphic crystal growth is often hampered by later modification at peak or post peak conditions. Numerous occurrences of textural sector zoning in garnet have been reported (e.g., Andersen, 1984; Burton, 1986; Rice and Mitchell, 1991; Wilbur and Ague, 2006). Compositional sector zoning in metamorphic crystals is well known in staurolite (e.g., Hollister, 1970) clinopyroxene, and zircon, among other minerals. However, reports of compositional sector zoning in garnet are rare, in spite of the large number of studies on garnet zoning. Oscillatory compositional zoning in garnet is relatively common and has been attributed to changing chemical or physical conditions during growth (e.g., Jamtveit, 1991; Stowell et al., 1996).

Compositional sector zoning in garnet includes radial variation along intersections of crystal faces belonging to one form (Argles et al., 1999; Wilbur and Ague, 2006) and variation along faces belonging to different forms (Kohn, 2004). Kohn (2004) reported compositional sector zoning in garnet from near the Main Central Thrust in Nepal. This zoning was attributed to differences in chemical partitioning between {211} and {100} faces. The accompanying oscillatory zoning largely found outside the sector zoned core was attributed to pulsed fluid flow and/or thrust loading. We report compositional sector and oscillatory concentric zoning in aluminum garnet from the Chiwaukum Schist in the North Cascades of Washington. Compositional zoning in this garnet is inferred to be a result of combined selective adsorption and kinetic attachment mechanisms during rapid crystal growth that was likely a product of reaction overstepping. Internal changes from sector to oscillatory zoning during growth are attributed to cessation of crystal growth on dodecahedral faces and later growth on trapezohedral faces. This change may have occurred during decreased overstepping of equilibrium reaction temperatures.

Geological Setting

The North Cascades crystalline core is the southernmost exposure of the Coast Plutonic Complex in Washington (Fig. 1). The southern core is segmented into the Chelan Mountains (northeast) and Wenatchee (southwest) blocks by the Entiat fault. Major deformational and metamorphic events are summarized in Stowell and others (2007). The southern Wenatchee block experienced at least three metamorphic events, M_1 to M_3, (Evans and Berti, 1986; Evans and Davidson, 1999; Paterson et al., 1994; Plummer, 1980; Stowell et al., 2007). The earliest metamorphic minerals (M_1) predate intrusion of Late Cretaceous plutons, including the Mount Stuart batholith. Andalusite and less common cordierite near the Mount Stuart batholith~~,~~ are interpreted as contact metamorphic in origin and define the low pressure M_2 event (Evans and Berti, 1986; Evans and Davidson, 1999). Metamorphic rocks north of the Mount Stuart plutons in the Chiwaukum Schist and Nason Ridge Migmatitic Gneiss (NRMG) contain sillimanite or kyanite, and do not contain andalusite or cordierite. Petrographic, thermobarometric, (e.g., Evans and Berti, 1986; Evans and Davidson, 1999) and geochronologic data (e.g., Stowell and Tinkham, 2003) indicate that these mineral assemblages postdate much or all of the Mount Stuart batholith and define a medium- to high-pressure metamorphic event (M_3) that is regional in extent. Stowell and others (2007) provide a paleobaric gradient, with higher pressures to the NE, incorporating new data and those from Evans and Davidson (1999). Garnet with complex zoning discussed here was sampled from the NRMG on the flank of Labyrinth Mountain near the 6 kbar M_3 isobar within ca. 250 meters of gneissic granodiorite sills along the northern edge of the Mount Stuart batholith (Fig. 1). Large subhedral to euhedral garnet crystals ranging up to ca. 1 cm in diameter are localized adjacent to the sills; however, smaller <5 mm garnet is near ubiquitous in schist outside the narrow <2 m zones adjacent to the sills. The large and small porphyroblasts are wrapped by the schistosity (S_e) and include a low density of inclusions defining an internal foliation (S_i), which varies from subparallel to almost normal to S_e.

Inclusions include quartz, biotite, and less abundant ilmenite, epidote, and plagioclase. S_i is interpreted to correlate with crenulated schistosity identified nearby and S_e likely correlates with a later crenulation cleavage (Bulman, 2005). These spatial and textural relations are interpreted to indicate that both large and small garnet porphyroblasts grew synchronous with sill emplacement during development of S_e and after early deformation now preserved as S_i.

Methods

Quantitative mineral compositions, backscattered electron images, and X-ray maps were collected with the JEOL 8600 electron probe microanalyzer at the University of Alabama using wavelength dispersion spectrometry. Major element analyses were collected with a 1 µm diameter beam at a current of 20 nA under a 15 kV accelerating potential. Raw counts from characteristic X-ray peaks were converted to weight percent oxides by comparison to natural mineral and synthetic standards, using the CitZAF correction technique of Armstrong (1984). Count times ranged from 30 to 45 seconds. Backscattered electron images and X-ray maps were collected using Geller Scientific DPict software to produce tiled raster maps. Maps were produced with beam currents ranging from 100-300 nanoamps, a pixel size of 2 microns, and count times of 50 milliseconds per pixel.

Electron back-scatter diffraction (EBSD) data were collected on the CamScan X500 Crystal Probe in the Department of Earth and Ocean Sciences at the University of Liverpool. The samples were SYTON polished to remove remnant damage in their surfaces from mechanical polishing and then given a very thin carbon coat to reduce charging. An accelerating voltage of 20 kV and a beam current of 5 nA allowed collection of electron backscatter patterns which were then interpreted using Channel v5 software from Oxford Instruments. Spatial resolution of the technique is better than 0.5 µm while mean angular deviation of the derived crystal lattice is better than 1°. Orientation contrast (OC) images revealed that individual garnet crystals did not have mis-oriented lattices, confirmed by mapping the lattice orientation of the sector zoned core of a garnet (960 x 1424 µm at a 16 µm grid spacing) to reveal a 0.39° mean misorientation of the lattice, which is within error of the method. Thus, lattice orientation data were collected at a relatively small number of points rather than by mapping a grid of points across each garnet.

Garnet Compositional Zoning

Sector zoning is used here to refer to compositional zones that are systematically related to crystallographic orientations in the crystal. Therefore, these zones can be directly related to the external crystal faces forming during growth. Sector and oscillatory zoning described here is from a single sample - 03NC143 - from the Chiwaukum Schist near Labyrinth Mountain. Observations from this sample were made from 12 garnet porphyroblasts observed in two 2.6 x 4.6 cm polished rock tabs and 1 larger garnet separated from the matrix of mica schist. Garnet from nearby schist from Heather Lake and elsewhere in the Wenatchee block show few or none of the compositional zoning features described for 03NC143. For example, garnet from Heather Lake shows no oscillatory and no sector zoning (Stowell et al., 2007), and one sample of garnet from Nason Ridge (02NC3) shows outer oscillatory zoning, but no sector zoning (Zuluaga, 2005).

Garnet is subhedral to euhedral and crystals range up to 0.7 cm in diameter. Compositional zoning determined for 5 garnet grains indicates that complex zoning is common to most or all crystals from the sample. Garnet crystals have sharp, but low amplitude (ca. 0.006 mole fraction) boundaries between Ca-rich and Ca-poor compositional zones that vary from sector zones and less systematic patchy zones to oscillatory concentric zones (Fig. 2). Iron, Mg, and Mn are concentrically zoned (Fig. 2). However, both Fe and Mg show small amounts of zoning that is opposite to that of Ca. Manganese does not show any sector, patchy, or oscillatory zoning in all of the garnet examined. Instead, this zoning is simply concentric in nature with decreases from ca. 0.104 to 0.009 in spessartine mole fraction from core to rim (Fig. 3). Iron and Mg are also concentrically zoned, but increase from the core toward the rim. In addition, the ratio of Mg to Fe + Mg (Mg/(Mg+Fe)) gradually increases from the core toward the rim. Manganese, Mg, Fe, and Mg/(Mg+Fe) or Mg# all show small amplitude reversals in zoning about 0.2 mm from the rim. The decreasing Mn and increasing Mg# indicate that zoning resulted from growth partitioning between garnet and matrix (Hollister, 1966) followed by minor modification by diffusion near the rim.

Low Ca zones (Fig. 2) increase in width outward from the apparent center of the crystal, then decrease in width and pinch out within the crystal along the projected boundary of trapezohedral faces {211} that dominate the external form. The <110> orientation for the axes of the low Ca zones, subsequently referred to as ‘petals’, is normal to dodecahedral faces {110} that are not part of the present external crystal morphology, which comprises {211} faces. Crystallographic orientations, determined by EBSD, from high and low Ca zones are identical clearly indicating that these are single garnet crystals not crystal aggregates. EBSD also confirms that the low Ca petals are oriented along dodecahedral <110> sectors and higher Ca zones are oriented along trapezohedral <211> axial sectors (Fig. 3).

Oscillatory zoning is common to the outer portions of all garnet observed in Ca K_{α} X-ray images from sample 03NCGB143 (Figs. 2 and 3). These zones are concentric with magnitudes of 0.006 to 0.012 mole fraction grossular and typical wavelengths of 0.05 to 0.15 mm (Fig. 3). Oscillations clearly outline the outermost trapezohedral {211} faces. Small-scale variations of grossular within the low Ca petals suggest that oscillations in Ca uptake by the crystals may have occurred throughout variations in growth on {110} and {211} faces.

Garnet compositional zoning determined for 5 garnet crystals from one rock tab (Fig. 2) and for one additional crystal illustrate that complex zoning may be common to most if not all crystals from the sample. These 2d slices of different crystals show internal sector, external oscillatory, and local patchy Ca zoning. Eight slices through a single crystal (Fig. 4) indicate that 3 dimensional compositional zoning is complex and that not all compositional zoning can be readily classified as sector or concentric oscillatory in nature. Patchy zoning, locally developed in garnet displayed in Figure 2, can be identified in most sections through the garnet shown in Figure 4. The patches vary from broad equidimensional to thin elongate areas. Elongate patches locally follow trails of inclusions and/or fractures, and in other cases follow boundaries between trapezohedral faces (Fig. 4). Patches truncate oscillatory zones and no sign of oscillatory compositional changes has been identified within patches.

Crystallographic orientations obtained by EBSD for 11 garnet crystals in situ indicate similar lattice orientations for all crystals within two ca. 4.5 x 2.5 cm slabs; especially so for the five garnets in Figure 5 but less so for the six garnets in Figure 6 where the <100> directions appear to have a small circle distribution perhaps reflecting some post-growth rotation about a common axis. Individual garnet lattice orientations appear related to the orientation of their S_i schistosity whereby two of the garnet <100> directions define a direction parallel to the trace of S_i in the garnet, implying a relationship between a {100} plane and S_i in the garnet. Robyr (2007) has described a similar relationship between garnet lattice orientation and included S_i, although garnet described here does not show the later sigmoidal deformation features described by

Robyr. This preferred orientation is compatible with the suggestion that garnet lattice orientation may not be random and can be controlled by foliation orientation during nucleation and/or deformation (e.g., Robyr et al., 2007).

Compositional sector zoning in garnet from the Chiwaukum Schist is grossly similar to that reported by Kohn (2004) and portrayed, but not elaborated on, in Wilbur and Ague (2006). However, zoning shown in these publications is considerably less regular and appears to be less closely related to external crystal form. These two occurrences may be less well developed or poorly preserved examples of the sector zoning described here. Alternately, they may have formed by other processes. The garnet sector zoning described here is analogous to sector zoning of As and Ag in pyrite controlled by {110} and {111} growth (Chouinard et al., 2005). In pyrite, the {110} faces were found to preferentially incorporate trace amounts of As and Ag.

Metamorphic Conditions

Metamorphic conditions have been estimated from thermobarometry and isochemical P-T phase diagram sections constructed in the MnNCKFMASHT system (Stowell et al., submitted). Peak metamorphic conditions were estimated for the sector zoned garnet sample (03NC143) and for a nearby sample (03NC19A).

Estimates for peak metamorphism range from 610 to 690ºC and 6.5 to 7.0 kbar (Stowell et al., submitted). Mineral textures, thermobarometry, and P-T phase diagram sections indicate a clockwise P-T-t path, which begins in the andalusite stability field at ca. 3 kbar and 510ºC, extends up pressure to ca. 6.5 kbar and 600ºC, and continues on a near isobaric path into the sillimanite field ca. 670ºC. The pressure and temperature estimates for Labyrinth rocks are in good agreement with those from nearby rocks in the Wenatchee block (Stowell et al., 2007).

Timing of Garnet Growth and Rates of Tectonic Processes

The timing of garnet growth is tightly constrained by garnet Sm-Nd isotope ages. Two samples from the immediate area have been dated: 03NC143, containing compositional sector zoning described here, and 03NC19A, which does not show sector zoning. Multiple garnet fractions and whole rocks define near identical isochron ages of 90.1±1.5 and 90.2±1.5 Ma, respectively (Stowell et al., submitted). The ages are indistinguishable (within uncertainty) from

U-Pb zircon ages of 91.0±1.7 and 90.6±1.8 Ma (Stowell et al., submitted) for the two adjacent orthogneiss bodies (Fig. 1). The closest zircon U-Pb age for the Mount Stuart batholith near Labyrinth Mountain is 96.8±1.8 Ma (Stowell et al., submitted). $^{40}Ar/^{39}Ar$ biotite ages for the Mount Stuart batholith and the Chiwaukum Schist in the Mount Stuart aureole are 87.2±0.4 and 86.2±0.4 Ma, respectively (Matzel et al., 2004).

Large, >1 cm, garnet porphyroblasts are restricted to rocks adjacent to orthogneiss in the Labyrinth area; however, smaller garnet porphyroblasts are common throughout the Chiwaukum Schist and NRMG. This association of large garnet porphyroblasts within pluton aureoles is common around plutons and to regions intruded by numerous dikes and sills (e.g., NRMG) in the North Cascades. The spatial restriction of large garnet to contact zones and the indistinguishable metamorphic garnet and igneous zircon ages are compatible with growth of large porphyroblasts of garnet in response to heat input from intrusion of the orthogneiss.

The differences in age between intrusion of the Mount Stuart pluton at pressures compatible with andalusite stability, metamorphism at kyanite and sillimanite conditions, and biotite cooling allow estimation of heating, loading, and cooling rates. Thermobarometric and geochronologic data for the Heather Lake area, about 5 km northwest of Labyrinth Mountain (sample 96NC67 in Stowell et al., 2007), indicate that Mount Stuart intrusion, ca. 96 Ma (Stowell et al., submitted) occurred at andalusite stability – P < ca. 4 kbar and < 550ºC, and that subsequent regional M_2 metamorphism was at ca. 6 kbar and 670ºC. The 5.6 m.y. age difference between the Mount Stuart batholith and garnet from Heather Lake, temperatures for andalusite growth and peak metamorphism require a heating rate of >20ºC /m.y. Assuming a closure temperature of 300ºC for biotite, the garnet ages of ca. 88 Ma at Heather Lake (Stowell et al., 2007) and the biotite cooling age require a cooling rate of 185ºC/m.y. Similar data set for the Labyrinth area (Stowell et al., submitted) indicates heating, loading, and cooling rates of ca. 11ºC/m.y., 0.6 kbar/m.y., and 67ºC/m.y., respectively. Clearly rates for heating, loading, and cooling were rapid throughout this part of the Wenatchee block.

Discussion

Garnet sector zoning is interpreted to result directly from differential incorporation of Ca during growth involving dodecahedral {110} and trapezohedral {211} forms. In this interpretation, the {110} faces incorporated less Ca than the adjacent {211} faces and thus the Ca petals can be used to infer the crystal morphology during growth. The {110} and {211} forms contributed to the crystal habit during early growth, then {110} diminished in importance until {211} became the prevalent form as seen in the present day external crystal morphology. Subsequent growth of garnet on trapezohedral faces did not produce further sector zoning, but allowed development of oscillatory Ca zoning. The development of sector zoning depends on the relative rates of growth and lattice diffusion. The specific properties of the interfacial regions between the crystal and its growing medium are responsible for the origin of intersectoral differences (Watson and Liang, 1995). These differences are preserved only if the growth rate is faster than the lattice diffusion rate. When preserved, the intersectoral differences are manifested as selective enrichment of one or more components on some growth surfaces (e.g., enrichment of Ca on {211} relative to {110}). The diffusion of Ca in garnet is slower than that of Fe, Mg, and Mn (Chakraborty and Ganguly, 1992); therefore, intersectoral differences in Ca content is most likely to be retained during the growth of the crystals while sector variation in other components may not be preserved at the peak metamorphic conditions experienced.

Differential incorporation of Ca into the {110} and {211} faces could result from kinetic and/or adsorption mechanisms (e.g., Shtukenberg et al., 2009). The latter was termed “selective adsorption” by Hollister (1970) and has been suggested to dominate sector zoning in crystals grown in aqueous fluids (Shtukenberg et al., 2009). The compositional sector zoning in Chiwaukum garnet is inferred to have developed during early simultaneous growth of {110} and {211} faces and is interpreted to result from differential incorporation of Ca on the {211} faces. The trapezohedral faces incorporated a greater amount of Ca than the adjacent dodecahedral faces. This growth may have followed the rapid face growth-edge re-entrant model described by Rice (2007). In this case, low Ca zones represent the rapidly growing {110} faces and the intervening higher Ca zones are re-entrants. Alternatively, the higher Ca zones represent {211} faces that grew simultaneously with {110} faces. In this case, {211} faces expanded in area at the expense of {110} faces during initial crystal growth, producing the petals which widen outward (Figs. 2 and 3). Both garnet growth interpretations require a change in growth rates of faces in order to explain decreasing low Ca petal width toward the outer sections of the garnet. The edge re-entrant model requires that {110} faces initially grew rapidly, then more slowly in order to produce low Ca petals. On the other hand, the rapid {211} growth interpretation requires a reversal of relative growth rates with initial rapid growth, followed by decreasing growth rates on {211}, and lack of {110} faces during final crystal growth. The data presented here do not allow for an unambiguous conclusion regarding a kinetic versus adsorption mechanism for the observed sector zoning. However, the restriction of garnet sector zoning to contact zones with orthogneiss and the rapid growth and cooling documented for these rocks is compatible with a kinetic influence on the development of compositional sector zoning.

Oscillatory zoning is relatively common in a wide variety of minerals (Shore and Fowler, 1996). The small-scale oscillatory zoning of Ca in Cascades garnet occurs in a concentric fashion parallel to both {110} and {211} crystal faces. Therefore, it is inferred to result from matrix processes which could be entirely external or be related to the kinetics of rapid crystal growth (Kohn, 2004). This type of zoning has been attributed to 1) an external control model of cyclic changes in temperature, pressure, or fluid composition, or 2) a kinetic model of cyclic, presumably rapid, crystal growth with associated depletion of reactant elements in the surrounding matrix. The Cascades schist occurs in regional metamorphic rocks that are likely to have been partly heated by intrusion of dikes and sills common in the NRMG. Kohn (2004) considered kinetic and external processed to explain oscillatory zoning of Ca in Himalayan garnet near the Main Central Thrust. No significant synmetamorphic fault or shear zones have been identified in this part of the Cascades; therefore, shear heating and fluid pulses related to heterogeneous fault slip are unlikely causes for the observed oscillatory zoning. Geochronologic results indicate that metamorphism occurred over a short time interval, and that heating and subsequent cooling were rapid. Therefore, disequilibrium and/or overstepping are possible explanations.

Patchy Ca zoning could be modified sector zoning, replacement/recrystallization driven by fluid infiltration, or a poorly understood growth phenomenon. The local association with fractures is most compatible with an origin that postdates garnet growth. However, association with inclusions is also compatible with a local disequilibrium growth mechanism. The elongate patches that relate to no obvious crystallographic orientation are somewhat similar to those described around mineral and fluid inclusions in garnet (Hames and Menard, 1993; Whitney, 1991). Therefore, this patchy zoning is likely to result from similar fluid assisted processes. However, the elongate, radial orientation, and interior occurrence of these zones allows the possibility that the modification occurred during porphyroblast growth.

Preservation of compositional boundaries with variation of <0.006 mole fraction grossular across distances of <0.1 mm within metamorphic rocks that were heated to ca. 650ºC requires that heating, peak temperatures, and cooling were rapid. Diffusion coefficients for calcium in garnet (Carlson, 2006) and path-dependent diffusion models for garnet growth and zoning (Caddick et al., 2010; Florence and Spear, 1991) indicate that heating and cooling rates must be rapid (≥100ºC/m.y.) and that the duration of metamorphism must be less than ca. 10 m.y. for preservation of compositional zoning in small garnets that reach >600ºC. Metamorphism of the Chiwaukum Schist, perhaps similar to many regional metamorphic rocks, is likely a result of regional "Barrovian" style heating combined with localized heat input from plutonic rocks. In the Chiwaukum rocks, this led to rapid heating, short lived metamorphism, and preservation of delicate compositional zoning in the garnet influenced by intrusive heating. The thermobarometry and geochronology discussed above indicates that heating rates were locally >20ºC/m.y. and that cooling rates were ca. 65 to 185ºC/m.y. Garnet grew at T >550ºC, based on phase diagram sections (Stowell et al., submitted); therefore, the total duration of time in which temperatures exceeded those of initial garnet growth must have been considerably less than 3 m.y. based on the difference between garnet Sm-Nd and biotite ^{40}Ar/^{39}Ar ages from nearby.

Rapid growth is inferred from the development and preservation of compositional sector zoning in garnet. Such rapid growth would normally be expected to favor poikiloblastic textures because the rapidly advancing crystal faces would likely trap inclusions, minimize the effects of increased surface free energy, and negate potential diffusion through the porphyroblast. These inclusions would presumably be phases that did not participate in prograde metamorphic reactions, excess reactant phases, or products of the garnet growth reaction. However, garnet from the Labyrinth area contains only a modest number of mineral inclusions (Figs. 2, 3, 4, 5 & 6). These are dominantly quartz and biotite, which may have been products and reactants, respectively during prograde metamorphism and garnet growth (Spear, 1993).

There is a notable lack of compositional sector zoning elsewhere in the Chiwaukum Schist; however, similar oscillatory zoning in Ca and Mn has been found in the adjacent Nason Ridge Migmatitic Gneiss on Wenatchee and Nason ridges (01NC15b and 02NC03b in Stowell et al., 2007). These two garnet occurrences, like the one described here, are closely associated with sheets and dikes of orthogneiss; therefore, the importance of rapid heating and cooling seems likely for all the known occurrences.

Acknowledgments

Michael Bersch is thanked for extensive help obtaining mineral composition data and for stimulating discussion on the origin of compositional zoning. Financial support from United States National Science Foundation grants EAR-0207777 and EAR-0710922 to Stowell were essential for completion of this research.

Figures

Figure 1 Generalized geologic map of metamorphic rocks on the north side of the Mount Stuart batholith in the North Cascades Crystalline Core, Washington, USA. Major folds and TIMS U-Pb zircon ages for the Mount Stuart batholith are from Matzel et al. (2006). Garnet Sm-Nd ages are from Stowell et al., (submitted).

Figure 2 Backscattered electron image of a thin section from 03NC143, North Cascades WA. Inset figures are Ca K_{α} intensity maps showing Ca zoning ‘petals’ within garnet crystals. The low Ca petals appear as dark zones radiating out from the center. Inset X-ray maps are ca. 2x scale of thin section.

Figure 3 Garnet composition in a single grain from 03NC143. A. Ca K_{α} X-ray intensity map with central area of radiating petals and outer area of oscillatory zoning. B. Detail of electron probe microanalyzer analyses along lines that cross petals and outer oscillatory zones.

Figure 4 Ca K_{α} X-ray intensity maps for slices through a single garnet crystal from 03NC143, Labyrinth Mountain, Washington. The slice number and depth from initial surface is given on each X-ray map. The initial map was obtained on a surface near the crystal center. Note the radiating ‘petals’ and irregular linear to patchy zones, see text for discussion.

Figure 5 Back scattered electron images and crystallographic orientation pole figures (lower hemisphere) for garnet crystals in 03NCGB143-2 collected near Labyrinth Mountain, Washington. A. Slab The scale bar is 2 mm in all cases. All <100>

summarizes the crystallographic orientations of the five garnet crystals exposed in the sample surface.

Figure 6 Back scattered electron images and crystallographic orientation pole figures (lower hemisphere) for garnet crystals in 03NC143-y collected near Labyrinth Mountain, Washington. The scale bar is 2 mm in all cases. All <100> summarizes the crystallographic orientations of the six garnet crystals exposed in the sample surface.

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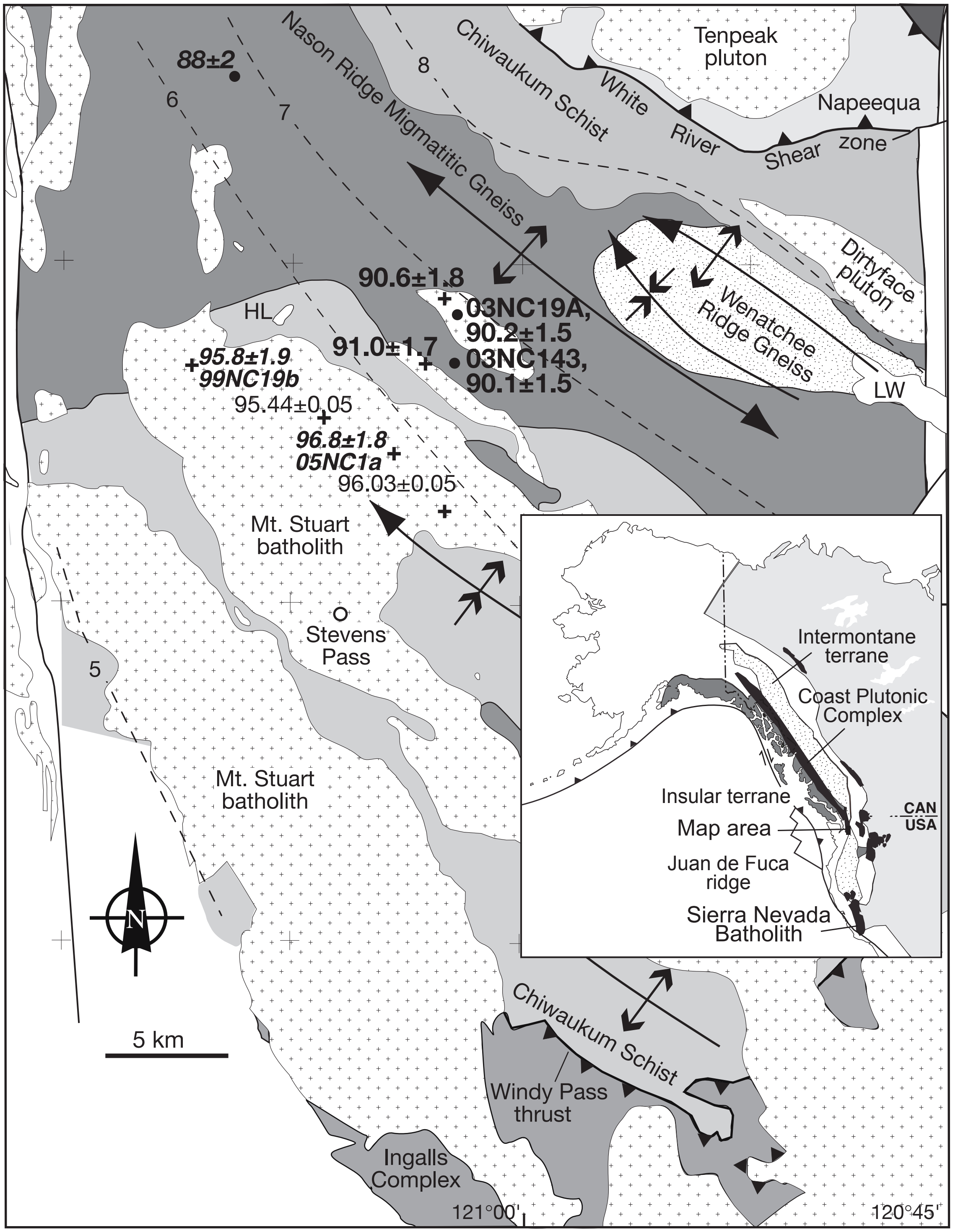

Figure 1. Geologic map of the Wenatchee block, WA.

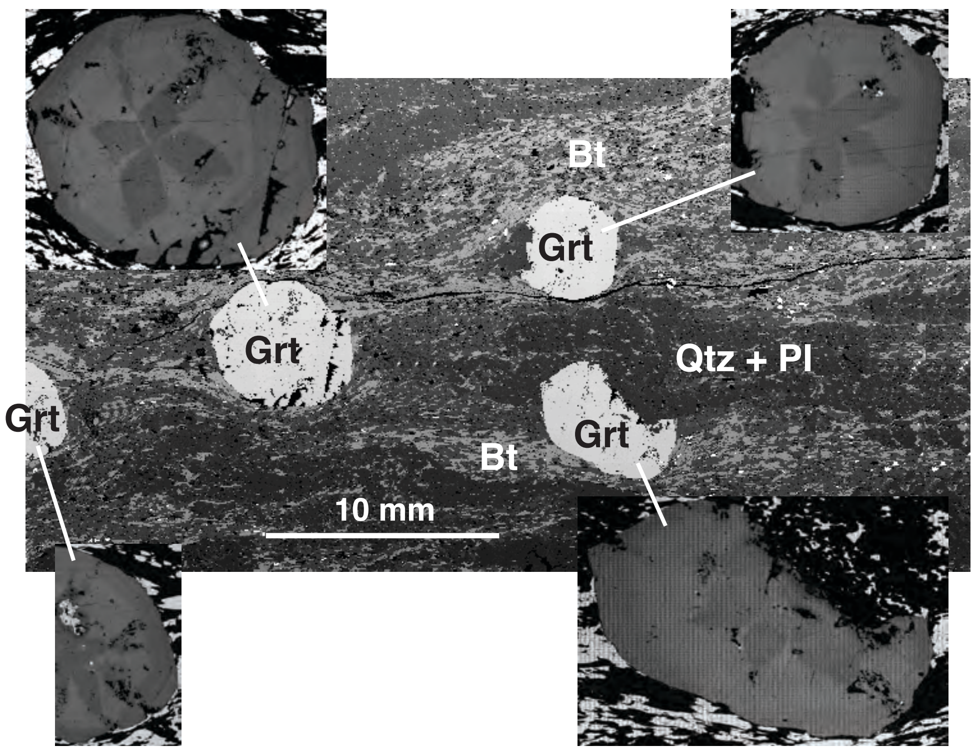

Figure 2. Garnet sector zoning, 03NC143.

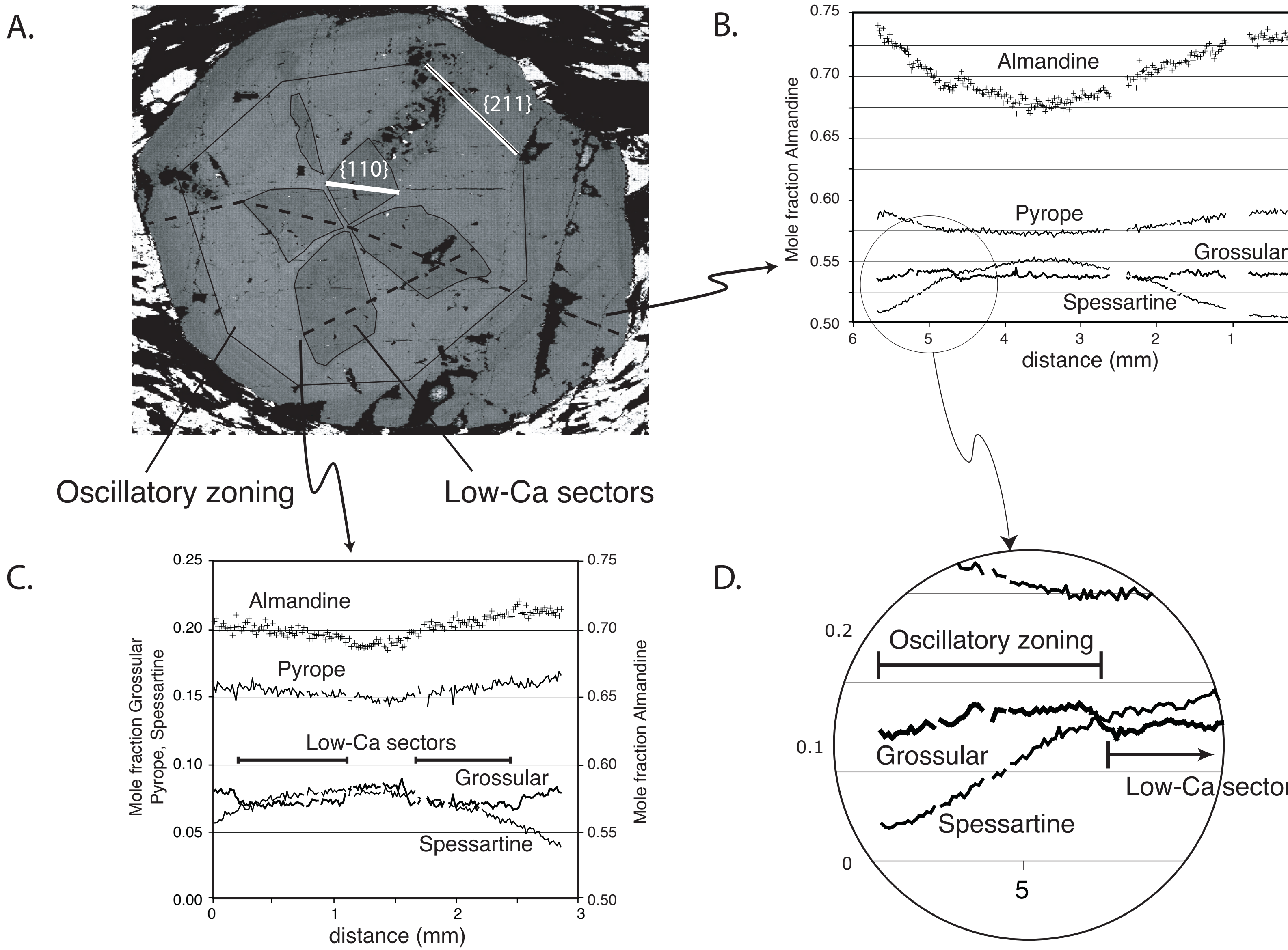

Figure 3. Garnet compositional zoning.

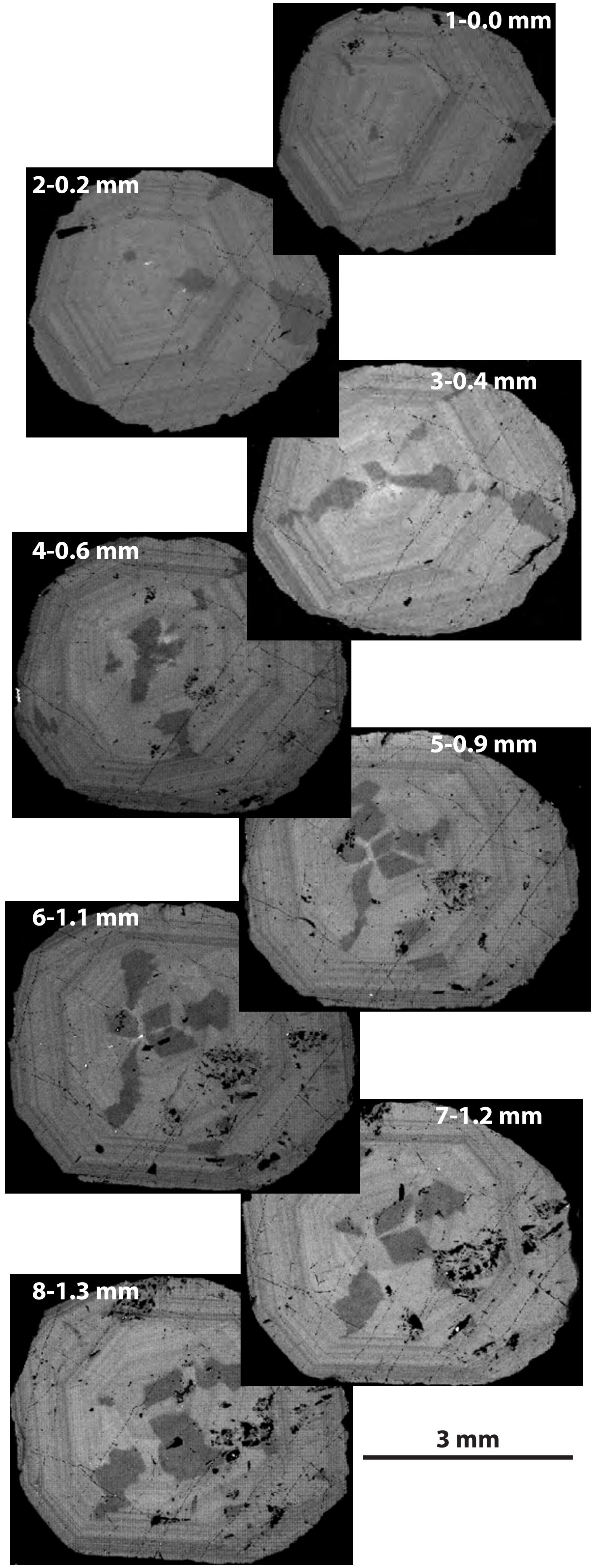

Fig. 4 Garnet Sector Zoning

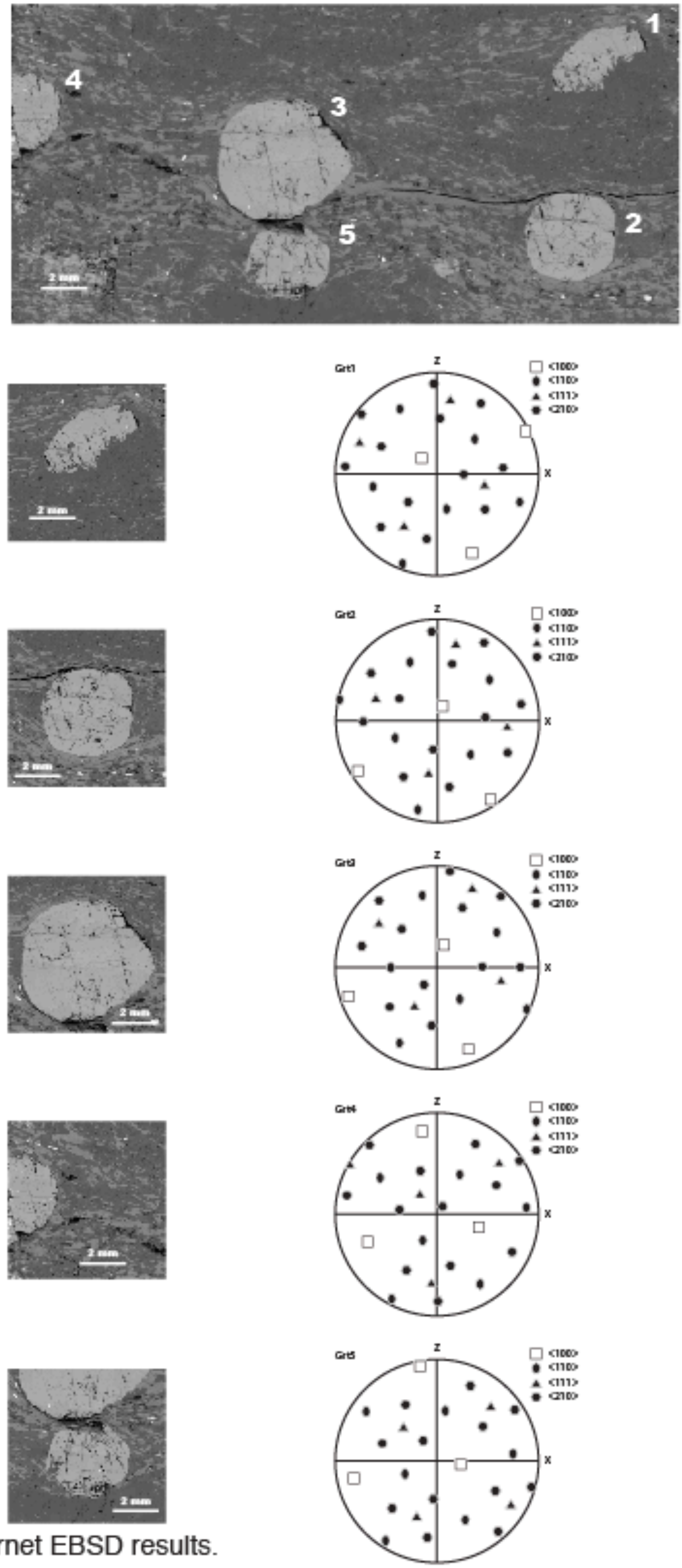

Figure 5. Garnet EBSD results.

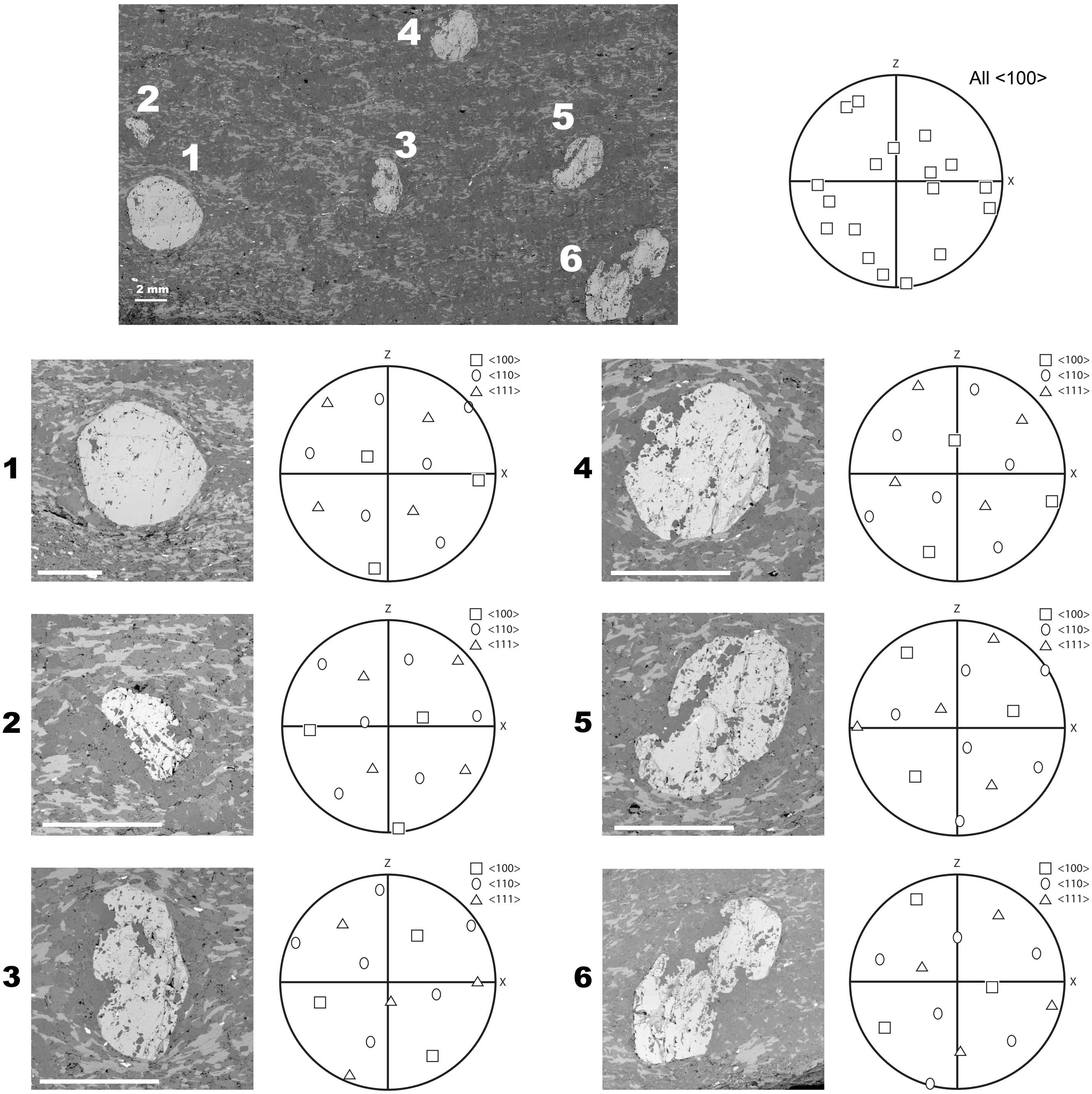

Figure 6. Garnet EBSD results.